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Safety Factor Profile Control in a Tokamak

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Preface

Tokamak reactors pose a myriad of interesting control challenges that have been tackled (with more or less success) over the past few decades. However, until recently, most of the control objectives were formulated in terms of one or a few scalar parameters or quantities (such as the plasma position, shape, total plasma current, etc.). In the last few years, more complex control problems, involving spatially distributed quantities (such as the plasma current density, temperature, magnetic field, etc.) that also evolve in time (and are thus represented by partial differential equations) have begun to appear in the literature. One of such problems is the control of the safety factor profile in a tokamak. This book presents a series of techniques and new methods applied to this control problem.

Although some results presented in this book are based on a series of articles by the authors, a great deal of effort was made to present them as a coherent body of work, as opposed to individual self-contained results, showing the logical progression of the research carried by the authors. Since this book should be accessible to the widest possible audience, we have opted to provide only sketches of proofs whenever possible in order to give to the reader the possibility to understand the main concepts without reducing the readability of the content.

In Chap. 1, we present a brief introduction to the control of thermonuclear fusion and highlight the interest of regulating the safety factor. A detailed explanation of the distributed reference model is provided in Chap. 2, as well as a general statement of the control problem and its main technical difficulties. A finite-dimensional control approach is proposed in Chap. 3, after discretizing the partial differential equations that model the poloidal magnetic flux evolution. The partial fulfillment of the control objectives obtained with this approach motivates the distributed approach that is followed in the rest of the book. Chapter 4 details the main theoretical results necessary for developing a distributed control law that can take into account space and time-variations of the transport parameters, together with some simulation results on a control-oriented simulator. Finally, Chap. 5 presents some extensions required for implementing the proposed scheme on a realistic scenario, along with simulation results on more complex, physics-oriented codes.

The authors wish to acknowledge the work of our co-authors and collaborators, who helped us to set the bases of the results presented in this book. We are thus grateful to Sylvain Brémond, Rémy Nouailletas, and Jean-François Artaud at CEA

in Cadarache, to Federico Felici and Olivier Sauter at EPFL, Lausanne, and to Didier Georges at GIPSA-Lab, Grenoble. Also, the useful comments of Hans Zwart, Jacques Blum (as opponents), Jonathan Lister, and Thierry Gallay (as examiners) on the Ph.D. dissertation of the first author have found their way into this book.

San Diego, CA, USA, June 2013
Grenoble, France

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Editors' Biography

Tamer Başar is with the University of Illinois at Urbana-Champaign, where he holds the academic positions of Swanlund Endowed Chair, Center for Advanced Study Professor of Electrical and Computer Engineering, Research Professor at the Coordinated Science Laboratory, and Research Professor at the Information Trust Institute. He received the B.S.E.E. degree from Robert College, Istanbul, and the M.S., M.Phil, and Ph.D. degrees from Yale University. He has published extensively in systems, control, communications, and dynamic games, and has current research interests that address fundamental issues in these areas along with applications such as formation in adversarial environments, network security, and resilience in cyber-physical systems, and pricing in networks.

In addition to his editorial involvement with these *Briefs*, Başar is also the Editor-in-Chief of *Automatica*, Editor of two Birkhäuser Series on *Systems and Control* and *Static and Dynamic Game Theory,* the Managing Editor of the *Annals of the International Society of Dynamic Games* (ISDG), and Member of Editorial and Advisory Boards of several international journals in control, wireless networks, and applied mathematics. He has received several awards and recognitions over the years, among which are the Medal of Science of Turkey (1993); Bode Lecture Prize (2004) of IEEE CSS; Quazza Medal (2005) of IFAC; Bellman Control Heritage Award (2006) of AACC; and Isaacs Award (2010) of ISDG. He is a member of the US National Academy of Engineering, Fellow of IEEE and IFAC, Council Member of IFAC (2011–2014), a past president of CSS, the founding president of ISDG, and president of AACC (2010–2011).

Antonio Bicchi is Professor of Automatic Control and Robotics at the University of Pisa. He graduated from the University of Bologna in 1988 and was a postdoc scholar at M.I.T. A.I. Lab between 1988 and 1990.

His main research interests are in:

- dynamics, kinematics and control of complex mechanical systems, including robots, autonomous vehicles, and automotive systems;
- haptics and dextrous manipulation; and

- theory and control of nonlinear systems, in particular hybrid (logic/dynamic, symbol/signal) systems.

He has published more than 300 papers on international journals, books, and refereed conferences.

Professor Bicchi currently serves as the Director of the Interdepartmental Research Center "E. Piaggio" of the University of Pisa, and President of the Italian Association or Researchers in Automatic Control. He has served as Editor-in-Chief of the Conference Editorial Board for the IEEE Robotics and Automation Society (RAS), and as Vice President of IEEE RAS, Distinguished Lecturer, and Editor for several scientific journals including the *International Journal of Robotics Research*, the *IEEE Transactions on Robotics and Automation*, and *IEEE RAS Magazine*. He has organized and co-chaired the first World Haptics Conference (2005), and Hybrid Systems: Computation and Control (2007). He is the recipient of several best paper awards at various conferences, and of an Advanced Grant from the European Research Council. Antonio Bicchi has been an IEEE Fellow since 2005.

Miroslav Krstic holds the Daniel L. Alspach chair and is the founding Director of the Cymer Center for Control Systems and Dynamics at University of California, San Diego. He is a recipient of the PECASE, NSF Career, and ONR Young Investigator Awards, as well as the Axelby and Schuck Paper Prizes. Prof. Krstic was the first recipient of the UCSD Research Award in the area of engineering and has held the Russell Severance Springer Distinguished Visiting Professorship at UC Berkeley and the Harold W. Sorenson Distinguished Professorship at UCSD. He is a Fellow of IEEE and IFAC. Prof. Krstic serves as Senior Editor for *Automatica* and *IEEE Transactions on Automatic Control* and as Editor for the Springer series *Communications and Control Engineering*. He has served as Vice President for Technical Activities of the IEEE Control Systems Society. Krstic has co-authored eight books on adaptive, nonlinear, and stochastic control, extremum seeking, control of PDE systems including turbulent flows, and control of delay systems.

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